

Case Study Abstract

In Situ Enhanced Soil Mixing, U.S. Department of Energy, X-231B, Portsmouth Gaseous Diffusion Plant, Piketon, Ohio

Site Name: U.S. Department of Energy (DOE), Portsmouth Gaseous Diffusion Plant X-231B	Contaminants: Chlorinated Aliphatics - 13 VOCs were identified in the soil at PGDP - Most prevalent VOCs were Trichloroethene (TCE), 1,1,1-Trichloroethane (TCA), 1,1-Dichloroethene (DCE), and methylene chloride - Concentrations ranged from several hundred to several thousand $\mu\text{g/kg}$	Period of Operation: June 1992
Location: Piketon, Ohio		Cleanup Type: Field demonstration
Technical Information: Robert L. Siegrist, Prin. Inv., ORNL, (303) 273-3490 Vendors: Jim Brannigan, Millgard, (313) 261-9760 Steve Day, Geo-Con, (916) 858-0480	Technology: In Situ Enhanced Soil Mixing (ISESM) - ISESM consists of soil mixing combined with additional technology - Four additional technologies were demonstrated at PGDP: vapor extraction with ambient air injection (stripping); vapor extraction with hot air injection (stripping); hydrogen peroxide injection; and grout injection for solidification/stabilization - 12 soil columns, each 10 ft in diameter and 15 ft deep, were treated in the demonstration - One additional column was treated by hot air stripping to a depth of 22 ft - Another additional column was used for a tracer study	Cleanup Authority: State: Ohio EPA
SIC Code: 9711 (National Security) Others - information not provided		Points of Contact: Dave Biancosino, DOE, (301) 903-7961 Jim Wright, DOE, (803) 725-5608
Waste Source: Waste Treatment Plant/Disposal Pit (waste oil biodegradation units)	Type/Quantity of Media Treated: Soil - Detailed information provided on soil characteristics, including physical, chemical, and biological properties - Clay content ranged from 12 to 25% - 78% of VOCs were present in uppermost 12 ft of soil	
Purpose/Significance of Application: Application of ISESM to remediate fine-grained soils that are difficult to treat with other technologies alone; technology is particularly suited to shallow applications, above the water table.		
Regulatory Requirements/Cleanup Goals: - Closure plan required 70% mass removal - No RD&D permit was required		

Case Study Abstract

In Situ Enhanced Soil Mixing, U.S. Department of Energy, X-231B, Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (Continued)

Results:

- Soil mixing with each of the 4 additional technologies performed better than the 70% VOC mass removal requirement
- Soil mixing with ambient air stripping achieved >90% removal after 3.75 hrs of treatment
- Soil mixing with hot air stripping achieved >95% removal after 3.75 hrs of treatment
- Soil mixing with peroxidation achieved >70% removal after 1 hr of treatment
- Soil mixing with solidification achieved >90% capture after 1 hr of treatment
- Soil mixing with hot air (thermal) stripping was selected as the remedial option for the site, with cleanup and closure completed in 1994; 628 soil columns at a depth of 22 ft were treated in remediation

Cost Factors:

- Actual capital costs of \$1,956,000 were expended for the demonstration, including \$481,000 for labor and \$500,000 for vendor subcontracts
- Equipment operating costs during demonstration were estimated at \$20,000 per day
- Demonstration costs for all four technologies reported as ranging from \$150-200/yd³
- Hot air stripping costs were 5% greater than for ambient air stripping, but achieved cleanup goals faster

Description:

The X-231B waste management unit at the DOE Portsmouth Gaseous Diffusion Plant (PGDP) consists of two waste oil biodegradation areas. The unit was used from 1976 to 1983 for treatment and disposal of waste oils and degreasing solvents, and contributed to contamination of soil and shallow ground water with VOCs. Thirteen VOCs were identified in the soil, including TCE, TCA, DCE, and methylene chloride, at concentrations ranging from several hundred to several thousand $\mu\text{g/kg}$. The site consists of relatively low permeability soils with elevated clay content.

In situ enhanced soil mixing (ISESM) was demonstrated at the site in 1992. ISESM consists of soil mixing combined with an additional technology. The following four additional technologies were demonstrated at PGDP: vapor extraction with ambient air stripping; vapor extraction with hot air stripping; hydrogen peroxide injection; and grout injection for solidification/stabilization. Three demonstration soil columns were completed for each of the four technologies (12 total). The 12 soil columns were each 10 ft in diameter and 15 ft deep. One additional column was treated by hot air stripping to a depth of 22 ft, and a second additional column was used for a tracer study.

Performance results showed that all four technologies performed better than the 70% VOC mass removal requirement specified by the Ohio EPA. Removals ranged from >70% (for peroxidation) to >95% (for hot air stripping). Based on the results of the demonstration, hot air stripping was selected for site remediation, which was completed in 1994. In situ solidification was more complicated than originally anticipated due in part to difficulty in effectively mixing the dense clay soil in situ and delivering the proper volume of grout. In addition, the solidification process generated secondary liquid wastes from grout delivery trucks and equipment cleanup. An improved "grout-on-demand" system has been developed to minimize waste.

SECTION 1

SUMMARY

Technology Description

In Situ Enhanced Soil Mixing (ISESM) is a treatment technology that has been demonstrated and deployed to remediate soils contaminated with volatile organic compounds (VOCs). The technology has been developed by industry and has been demonstrated with the assistance of the U.S. Department of Energy's Office of Science and Technology and the Office of Environmental Restoration.

- ISESM encompasses a number of in situ soil treatment technologies that can treat contaminated soils, especially those of a fine-grained nature, which are difficult to treat with other remediation technologies. Contaminants are either removed from the soils or stabilized in place. The mixing process allows good access for reagent delivery to all soil particles and the interstices between particles. The technology is particularly suited to shallow applications, above the water table, but can be used at greater depths.
- ISESM technologies demonstrated for this project include:
 - ◊ soil mixing with vapor extraction combined with ambient air injection [Contaminated soil is mixed with ambient air to vaporize volatile organic compounds (VOCs). The mixing auger is moved up and down to assist in removal of contaminated vapors. The vapors are collected in a shroud covering the treatment area and run through a treatment unit containing a carbon filter or a catalytic oxidation unit with a wet scrubber system and a high efficiency particulate air (HEPA) filter.]
 - ◊ soil mixing with vapor extraction combined with hot air injection [This process is the same as the ambient air injection except that hot air or steam is injected.]
 - ◊ soil mixing with hydrogen peroxide injection [Contaminated soil is mixed with ambient air that contains a mist of diluted hydrogen peroxide (H_2O_2) solution. The H_2O_2 solution chemically oxidizes the VOCs to carbon dioxide (CO_2) and water.]
 - ◊ soil mixing with grout injection for solidification/stabilization [Contaminated soil is mixed as a cement grout is injected under pressure to solidify and immobilize the contaminated soil in a concrete-like form.]
- The soils are mixed with a single-blade auger or with a combination of augers ranging in diameter from 3 to 12 feet. Mixing is likely to be effectively applied to depths of 40 feet, although commercial vendors have worked at depths as great as 100 feet with the smaller diameter augers. Enhancements such as injection of heated air in combination with vapor extraction, injection of oxidants, or injection of grout are utilized based on the specific system selected for a particular site.

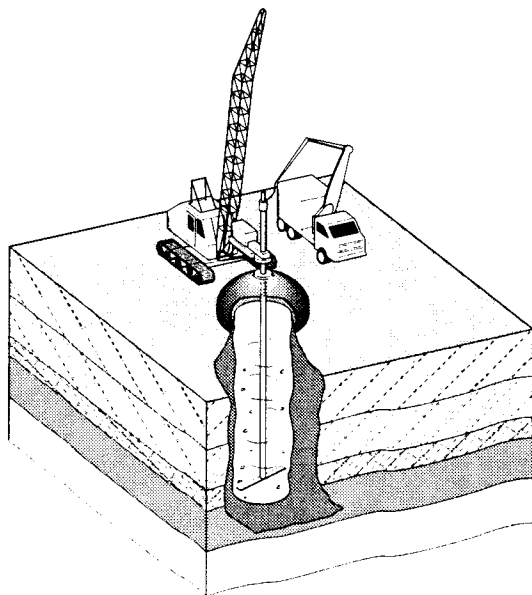


Illustration of the continuously mixed subsurface soil reactor concept. (Note: treatment agents are delivered through the mixing blade with emissions captured in the shroud covering the mixed region.) Rigs can have single or multiple shafts.



Technology Status

- In situ soil mixing, also known as deep soil mixing, shallow soil mixing, soil mixing wall, auger mixing, etc., has been used for a number of years in the construction industry. Cement grout is typically mixed with soil to create a foundation system or barrier wall. Soil mixing with stabilization (Geo-Con/IWT) was demonstrated under the EPA SITE Program in 1990 at a General Electric Shop in Hialeah Florida where soils were contaminated with PCB's.
- The above four ISES treatment technologies were selected for evaluation during a full-scale field demonstration at the Department of Energy (DOE) Portsmouth Gaseous Diffusion Plant (PGDP), near Piketon Ohio. The field demonstration was conducted at the X-231B Unit in June 1992. Replicated tests of in situ vapor stripping, peroxidation, and solidification were made in soil columns measuring 10 ft in diameter and 15 - 22 ft deep.
- The X-231B Unit was used from 1976 to 1983 as a land disposal site for waste oils and solvents. Soils beneath the unit were contaminated with VOCs, such as TCE at approximately 100 parts per million (ppm), and low levels of radioactive substances. The shallow ground water (12-14 ft depth) was also contaminated, and some contaminants were above drinking water standards. Approximately 78% of the VOCs were located in the upper 12 ft.
- Geologically the site contains low permeability sediments, composed of silt and clay deposits with hydraulic conductivities of less than one millionth of a centimeter per second ($K < 10^{-6}$ cm/s).
- A computerized data acquisition system linked to approximately 60 sensors enabled near-continuous monitoring of process operation and performance. Nearly 500 soil and gas samples were collected before, during, and after soil treatment for analyses of physical, chemical, and biological parameters. Soil matrix, soil vapor, and off-gas VOC measurements were made.
- The technology demonstration was a public/private partnership effort between Oak Ridge National Laboratory (six divisions), DOE-Portsmouth Field Office, Lockheed Martin Energy Systems at Portsmouth, University of Tennessee, Michigan Technological University, Chemical Waste Management, Millgard Environmental Corporation, Envirosurv, and NovaTerra.
- After the demonstrations were completed, the most effective of the four technologies, thermal vapor extraction, was selected as the remedial option for the site. Cleanup and closure of the site was completed in 1994. This innovative treatment technology resulted in a total cost savings of \$80 million as compared to traditional excavation and treatment approaches. Closure activities were completed by Geo-Con.
- A number of companies provide ISES technology commercially (see U.S. EPA VISITT database and DOE Commercial Environmental Cleanup, 1995). However, this demonstration was unique in that four different ISES technologies were compared at a single site.
- ISES will be demonstrated at the DOE Kansas City Plant in the spring of 1996. Mixing to a depth of 45 feet will be accomplished and additives such as potassium permanganate, lime and bionutrients will be tested.

KEY RESULTS

In situ treatment of VOCs in clay soils was effectively (>85% reduction) and rapidly accomplished at acceptable costs.

- Vapor stripping processes-ambient air and hot air injection:
 - ◇ Treatment performance improved with longer mixing times. 50% of the target VOCs were removed in approximately 90 minutes, whereas 92 to 98% of the contaminants could be removed in the top fifteen feet of soil if mixing were continued for 225 minutes.
 - ◇ Extension of the zone of treatment to 22-ft depth exhibited only a moderately reduced removal efficiency (i.e. average of approximately 88%).
 - ◇ Soil bacteria levels were increased by several orders of magnitude following ambient air stripping.



- In situ peroxidation:
 - ◊ In situ peroxidation was found to treat soil more rapidly than vapor stripping. VOC treatment efficiency was approximately 72% mass removal in 75 minutes to a depth of fifteen feet.
- In situ solidification:
 - ◊ VOC treatment efficiency was over 90%. Limited VOCs were removed in the off-gas during grout injection and mixing.
- In situ treatment of VOCs in clay-rich soils was rapidly accomplished (e.g., >15 cubic yards per hour [yd³/h]).
- Treatment costs for each of the four technologies was comparable, ranging from \$150 to \$200 per cubic yard for the demonstration. Further experience has brought treatment costs down (see cost section).
- Use of a hydraulic probe for soil sampling with on-site VOC analyses, followed by three-dimensional visualization, provided enhanced information compared with conventional sampling, off-site analyses, and routine data treatment.

CONTACTS

Technical

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Management

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Jim Wright, DOE Plumes Focus Area Implementation Manager, (803) 725-5608.

Commercial vendors

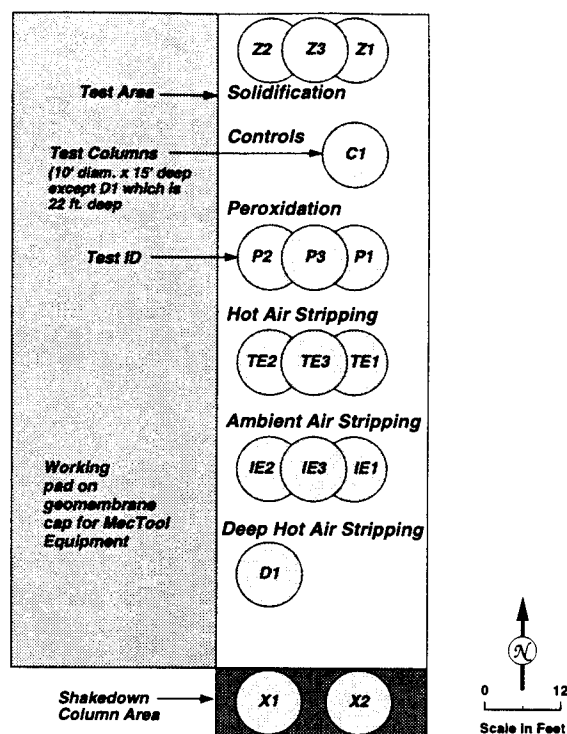
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SECTION 2

TECHNOLOGY DESCRIPTION



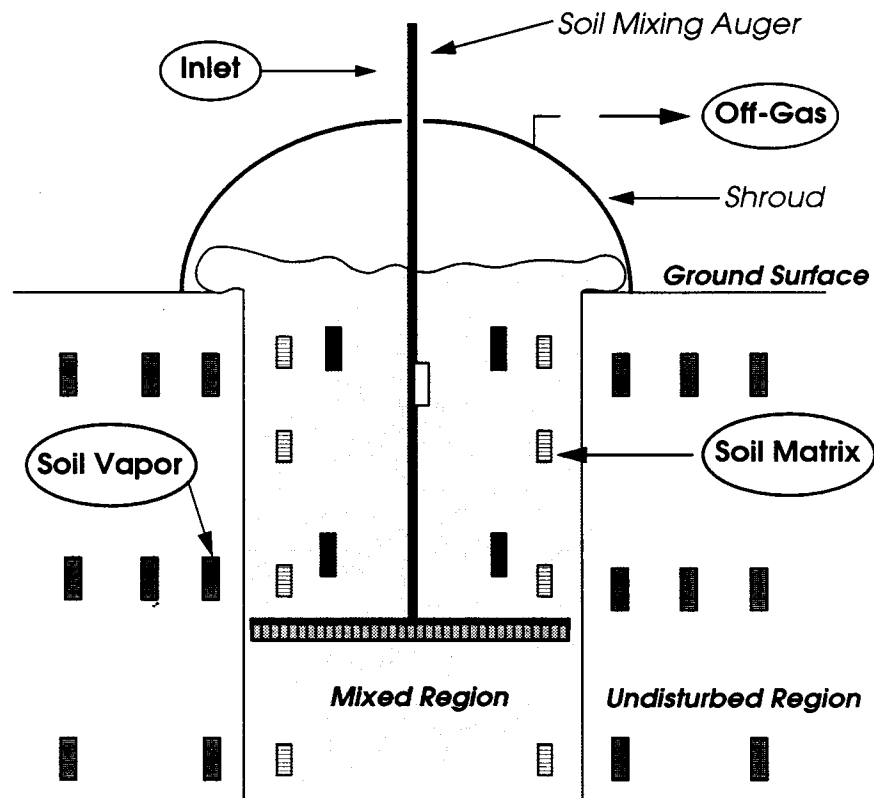
Schematic of the test site layout for the full-scale field demonstration in the X-231B unit.

Overall Process Description

- A mechanical system was employed to mix unsaturated or saturated contaminated soils while simultaneously injecting treatment or stabilization agents. The main system components include the following:
 - ◊ a crane-mounted soil mixing auger,
 - ◊ a treatment agent delivery system,
 - ◊ a treatment agent supply,
 - ◊ an off-gas collection and treatment system.
- The mixing system used in the demonstration was manufactured and operated by Millgard Environmental Corporation, Livonia, MI. It is comprised of a track-mounted crane with a hollow, Kelly bar attached to a drilling tool, known as the MecTool™, consisting of one or two, 3- to 5-ft. long horizontal blades attached to a hollow vertical shaft, yielding an effective mixing diameter of 6 to 10 feet. Depths of 40 feet can be achieved with this equipment. The 10-foot mixing diameter was used for this demonstration.
- Treatment agents were injected through a vertical, hollow shaft and out into the soil through 0.25 or 0.50 in. diameter orifices in the back side of the soil mixing blades. Treatment is achieved in butted or overlapped soil columns. Chemical Waste Management conducted the solidification/stabilization portion of the demonstration working in concert with Millgard Environmental Corporation.
- The ground surface above the mixed region was covered by a 14-ft. diameter shroud under a low vacuum to contain any air emissions and direct them to an off-gas treatment process. The off-gas treatment system consisted of activated carbon filters followed by a HEPA filter.
- Removal of VOCs was enhanced by moving the mixing auger up and down from 2 to 15 ft below ground surface during vapor stripping.



- For the demonstration, a total of 14 soil columns, each 10 ft in diameter, were treated.
 - ◊ Each of the four treatment processes were demonstrated in three soil columns, each 15 ft. deep. Two of each set of three columns were located in an undisturbed area, while a third, central column was placed to overlap the outer two by approximately 40%.
 - ◊ One column was treated by the hot air stripping to a depth of 22 ft.
 - ◊ A single column, 15 ft. deep, was used for a tracer study.
 - ◊ The operating conditions for the demonstrations are summarized in Appendix B.



Legend

- Pre- and post-treatment soil samples
 - Vapor implant in undisturbed soil, North/South of test column
 - Vapor implant in undisturbed soil, NE/SE of test column
 - Vapor implant in mixed soil
- 0 5
Scale in Feet

Profile view of a treated soil region and associated monitoring points.

- For the X-231B closure, a total of 628 soil columns with a depth of 22 feet were treated. The closure was completed by Geo-Con, using similar equipment.

SECTION 3

PERFORMANCE

Demonstration Plan

- The goal of the ISESM technology demonstration was reduction in the target VOCs in the treatment zone of at least 70%, to meet Ohio EPA performance standards.
- Primary monitoring and measurement activities included:
 - ◇ Pre-treatment and post-treatment soil sampling
 - temperature
 - VOCs
 - particle-bound radioactivity
 - ◇ In situ soil gas
 - temperature
 - pressure
 - VOCs
 - ◇ Operations data
 - treatment depth
 - processing times
 - flow rate
 - resource consumption

Treatment Performance

- A table of general observations of treatment performance for each of the four technologies is presented in Appendix B.

Hot Air Vapor Stripping

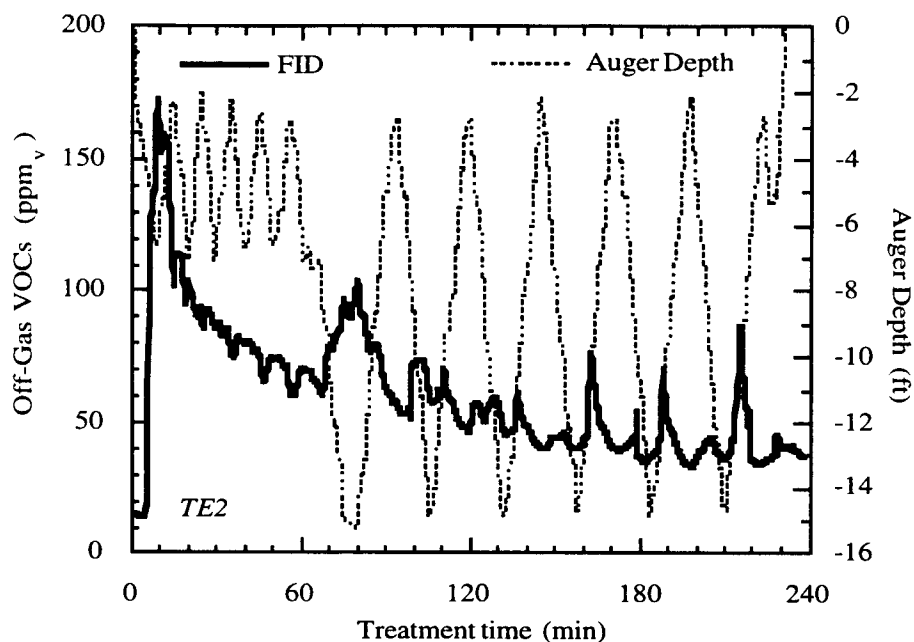
- Treatment performance for a 15-ft. soil column:

VOC Removal Efficiency (%)	Minutes of Operation
50	90
85	120-150
95-98	225

- VOC removal efficiency for the 22-ft. soil column was approximately 88%.
- The mass of VOCs removed as estimated by off-gas sampling generally was consistent with the reduction in soil VOCs estimated from pre-treatment and post-treatment sampling. These data indicated that VOCs were removed from the soil, rather than being forced into surrounding undisturbed soil. This assessment was confirmed by the absence of significant pressure or temperature effects on the unmixed region surrounding the treated columns.
- Off-gas temperatures increased from ~25 to ~40°C after 225 minutes of treatment. Warming of the soil matrix was demonstrated by using thermocouples. Seventy hours after completion of hot air injection, soil matrix temperatures were 34°C and 37°C at depths of 3.5 and 9 feet, respectively. After 140 hours, temperatures remained elevated above background.
- Mixing created a berm of soil of approximately 15% of the treated region above the treated volume for both vapor stripping and peroxidation.



- The figure below, illustrates the relationship between the position of the auger and the concentration of VOCs in the off-gas. The general decline in VOC concentrations with intermittent spikes suggested that VOCs were advectively removed from the gas-filled voids surrounding soil matrix clods while the auger passed through. Diffusion of VOCs from the soil matrix then replenished the gas-filled voids, which were later stripped during a subsequent pass of the auger.



Auger position and off-gas VOC concentration for hot air column TE2.

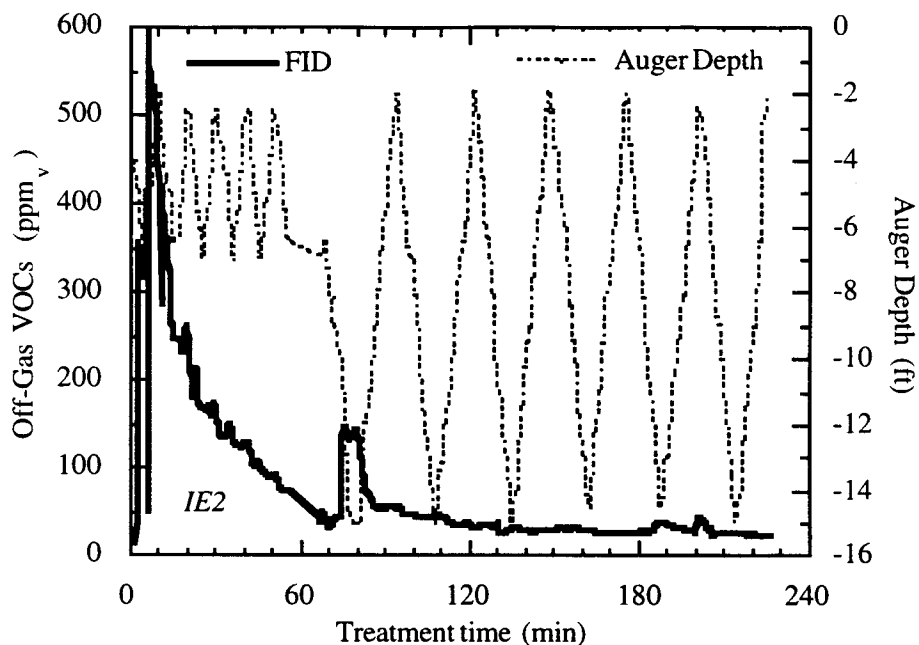
Ambient Air Vapor Stripping

- The treatment performance achieved with ambient air injection was similar but slightly lower than that achieved with hot air. VOC removal efficiency for a 15-ft. soil column:

VOC Removal Efficiency (%)	Minutes of Operation
50	90
85	140-180
92	225

- Temperature of the off-gas increased gradually from 15°C. initially to 30°C. after 225 minutes of treatment. This gradual increase in off-gas temperature is believed to be due to warming of the soil matrix. Thermocouples placed in the soil revealed elevated temperatures of as much as 37°C. Elevated temperatures persisted for more than 94 hours after treatment.
- The mass of VOCs removed as estimated by off-gas sampling generally was consistent with the reduction in soil VOCs estimated from pre-treatment and post-treatment sampling. These data indicate that VOCs were removed from the soil, rather than being forced into surrounding undisturbed soil.

- The figure below illustrates the relationship between the position of the auger and the concentration of VOCs in the off-gas.



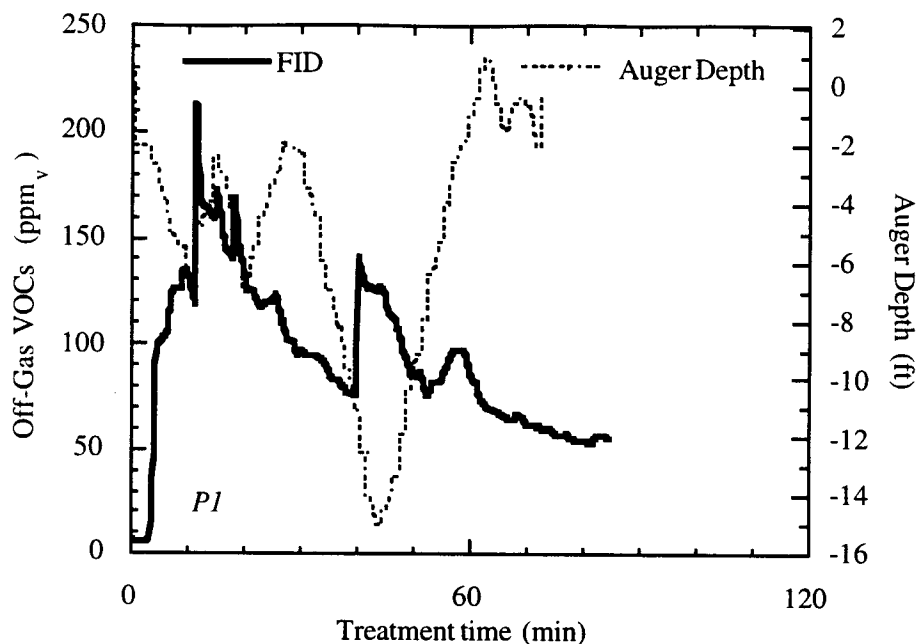
Auger position and off-gas VOC concentration for ambient air column IE2.

Peroxidation Destruction

- VOC removal efficiency for a 15-ft. soil column averaged approximately 72% after 75 minutes of operation. This removal efficiency is faster than that shown for vapor extraction.
- The apparent VOC treatment efficiency (total % removed) with peroxidation was below that achieved with both vapor extraction processes. This could have been due to:
 - ◇ pre-treatment VOC concentrations were relatively low.
 - ◇ in situ mixing only occurred for a short period of time (i.e., 60 min.).
 - ◇ off-gas collection system capacity was too low during the peroxidation test (system dysfunctioned).



- The figure below illustrates the relationship between the position of the auger and the concentration of VOCs in the off-gas.



Auger position and off-gas VOC concentration for peroxidation column P1.

- During the peroxidation test, the off-gas collection system malfunctioned yielding a flow rate of roughly 30% of the air injection rate. This could have adversely affected the VOC treatment efficiency by altering the extraction of VOCs as well as the distribution of the peroxide mist.

Solidification/Stabilization

- During in situ mixing and grout injection, the concentrations of VOCs in the off-gas were at least an order of magnitude less than that obtained from the columns treated by vapor extraction/air injection. Because grout was applied before soil mixing was initiated and because the grout application rate was rapid, little volatilization of VOCs is believed to have occurred as mixing proceeded.
- Total VOC concentrations in untreated soil ranged from 0.1 to over 500 mg/kg. Total VOCs in the uncured grout/soil mixture were markedly lower than in untreated soil when compared by depth. Analytical problems with measurement of VOCs in grout may be responsible for the uncertainty in the mass balance for the VOCs.
- Toxicity Concentration Leaching Procedure (TCLP) concentrations for regulated constituents were either not detected or were well below EPA's regulatory limits. A few examples of the data collected are provided in Table 3, Appendix B.
- A comparison of physicochemical properties of untreated and solidified soil are provided in Appendix B.
 - ◇ The average bulk density of untreated soil (1.95 g/cm³) was greater than that of the soil/grout specimens (1.78 g/cm³). The decrease in bulk density after solidification may be due to the initial high bulk density of a clay-rich sample, which is reduced as a result of mixing. Also, the reduction in bulk density may be a result of entrapment/entrainment of air in the grout during mixing.
 - ◇ The compressive strength values ranged from 390 to 5200 kPa (56 to 750 psig) and were inversely proportional to depth. Samples from the upper part of the core appeared to be highly grouted, while the deepest sample (13-14 ft.) appeared very fragile with a relatively small amount of grout material present. All values obtained, however, were greater than the currently accepted guideline of at least 340 kPa (50 psig).

- ◇ The hydraulic conductivity (K_{sat}) of cured grout/soil samples was two orders of magnitude greater than that of the untreated soil. This is probably due to disruption of the dense clay deposit as a result of mixing and increased porosity within the grout/soil mixture due to incomplete filling of the pores with grout.
- ◇ The pH of the grout/soil mixture (10.3-11.5) was significantly higher than that of the untreated soil (5.3-7.5), presumably due to the high alkalinity of the cement-based grout. The stabilized soil/grout mixture should be more stable to acid attack.
- ◇ Total volatile solids analyses revealed values ranging from 1.2 to 8.0 wt% throughout the solidified soil, with the values often lower than the corresponding value of the untreated soil column.
- The strengths and hydraulic conductivities measured are probably in error due to the sampling technique. Other projects using grout injection have demonstrated lower hydraulic conductivities and higher strengths.
- As a result of mixing the dense clay soil and injecting grout, an above-ground berm was created above each solidified column (approximately 1 meter high and equivalent to 30% v/v of the mixed region. The berms were eventually leveled out and compacted with vibratory equipment.



SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- In situ soil mixing is commonly used in the construction industry. In situ soil mixing for stabilization has been commonly used at sites with soil contaminated with organics, but is also recognized as appropriate for metals-contaminated soils.
- ISES with injection of hot air, ambient air, or hydrogen peroxide has been demonstrated to effectively remediate clay-rich soils contaminated with VOCs in the unsaturated zone.
- ISES is attractive for contaminated sites that contain low permeability soils that cannot be remediated using other technologies, such as in situ bioremediation. However, it can also be used in more permeable materials.
- ISES is attractive for relatively small sites.
- ISES requires surface access at all locations where soils are contaminated.

Competing Technologies

- ISES as applied to sites like the X-231B site at Portsmouth competes with the following baseline technologies:
 - ◊ excavation followed by on-site or off-site storage and/or treatment,
 - ◊ in-place containment by capping and slurry wall emplacement.

Other technologies that were considered for demonstration at the X-231B site are listed below.

Soil treatment technology	Technology description
In situ immobilization	Soil mixing by auger or jet system with addition of solidification/immobilization agent to solidify soil mass and immobilize VOCs and other contaminants in place.
In situ hot-air and/or steam stripping	Soil mixing by dual auger system with injection of hot air and/or steam to raise soil temperature and volatilize VOCs.
In situ electrokinetics	Application of electrical energy to the soil mass in situ with induced mobility of water and ions toward a capture electrode system.
In situ jet mixing and slurry reactor	In situ jet mixing with air or water to create an in-place slurry reactor that could be manipulated to achieve physical, chemical, or biological processes for removal/degradation of VOCs.
In situ EM/RF heating	In situ application of electromagnetic or radiofrequency energy to heat the soil mass in place and volatilize VOCs.
In situ (ex situ) hydrogen peroxide	Injection of hydrogen peroxide during soil mixing by a dual auger system or by jetting, or application ex situ. VOCs are chemically oxidized, physically stripped, and/or destroyed.
Ex situ thermal treatment	Excavated soil is processed by thermal treatment during which VOCs are volatilized, captured, and/or destroyed.
Ex situ immobilization	Similar to in situ process, except excavated soil is treated above ground in a tank or container.

Technology Maturity

- The 1992 technology demonstration brought together existing technologies into new configurations or systems so that they could be applied in situ in low permeable media.
 - For example, peroxidation destruction is commercially available for ex situ applications, however in situ treatment of soils is novel.
 - Solidification/stabilization is well established for inorganics, but some questions remained for its effectiveness on organics.



SECTION 5

COST

Introduction

- Information in this section was prepared from data provided in various project reports from the actual demonstration and from one of the vendors (Geo-Con). An independent cost analysis has not been performed.

Capital Costs

ISESM Actual Demonstration Costs (Jolley et al., 1991)

Task Description	Estimated Cost
Project Management	199,500
Technical Task Plan Preparation	15,750
Permits and Plans	42,000
Procurement	31,500
Treatability Studies	31,500
Performance Monitoring	73,500
Site Preparation and Equipment Installation	42,000
Data Evaluation and Document Preparation	42,000
Labor	481,000
Travel (for equipment installation and monitoring by the ORNL team)	50,000
Supplies	16,000
Materials and Subcontracts	40,000
Treatability Studies	150,000
On-Site Demonstration	
Plans and Permits	40,000
Site Preparation and-Equipment Set-up (included building a road to the site)	100,000
Demonstration (approximately 2 weeks of soil mixing and treatment)	150,000
Demobilization and Site Restoration (included recapping the site)	60,000
Vendor Subcontracts	500,000
Miscellaneous and Computer Support	124,000
Analytical Support, QA, Waste Management	150,000
Other (including G&A and GPS)	595,000
Total Actual Demonstration Costs	1,956,000



Demonstration Cost Analysis

- Costs for equipment operation during demonstration treatment of three regions to a depth of up to 15 ft. are estimated at ~\$20K/day.
- ISESM with a smaller auger blade would reduce equipment mobilization and demobilization costs.
- For the demonstration, soil mixing costs were the same for each treatment process with minor cost variation between processes based on required materials and equipment (\$150 to \$200/cy). Updated 1996 costs are estimated at \$120-175/cy or less. Further development of the technologies has shown that solidification is less costly than hot air injection.
 - ◇ Hot air vapor extraction costs were approximately 5% higher than for ambient air due to equipment; however, the process obtained similar performance goals faster. Treatment times (drilling/injection time only) for hot air stripping, deep hot air stripping and ambient air stripping were comparable and approximately 3 times slower than peroxidation and 5 to 7 times slower than in situ immobilization.
 - ◇ Additional costs are associated with required materials for peroxide destruction and solidification/stabilization, but both of these processes achieved treatment goals rapidly.
 - ◇ A technology selection table for the X-231B Site is located in Appendix C.

Vendor Cost Analysis

- Preliminary cost information is based on clean up of a contaminated site with the following characteristics:
 - Area to be Treated: ~29,000 sq. ft (~0.8 acres) [460-10ft or 720-8ft columns]
 - Depth of Contamination: from ground surface to 25 ft deep
 - Target Contaminants: VOCs
 - Target Clean-up Goal: 90% destruction/removal/immobilization (total soil VOC concentration of less than 1 mg/kg)
- Other assumptions include:
 - Mixing with stabilization assumes use of Portland cement 15% by weight. Ten columns per day are grouted. No offgas treatment is necessary for this application.
 - Hot air injection assumes 5 columns per day. Each column is mixed for one hour.
 - Jet mixing is calculated assuming using three-foot spacing on the columns. 3720 columns are required for treating the area. Eight columns per day are completed. Cement must be added at 25% by weight. Two single stem rigs are used for this application.
 - No estimate for air monitoring, sampling, and testing is included.
 - Security, utilities, grading, etc. are not included. Level D protective equipment is required and included.
 - Cost for work at a government facility may be 10 to 50% higher.
 - Costs are estimated by Geo-Con as of 1996. If the contract is written as performance based, additional mixing time should be priced on an hourly or cost-plus basis.

Technique	Schedule (Production Weeks)		Mobilization (\$)	Unit Costs (\$/cy)	
	8 ft.	10 ft.		8 ft.	10 ft.
Hot Air Injection	28.8	18.4	250,000	75	60
Stabilization	14.4	9.2	150,000	55	45
Jet Mixing	55.8		70,000	170	



SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- Early and continuous communication with the regulatory community is essential when assessing and determining the application of unproven or innovative technologies.
 - At the Portsmouth Gaseous Diffusion Plant, the regulators were brought in to work with the site managers to select options for closure of the X-231B site. This early involvement streamlined the process for regulatory approval of the technology demonstration and also the later closure of the facility.
 - Regulators in charge of ground water, surface water, RCRA, and the consent decree were all involved in the process.
- The technology demonstration was conducted by modifying the closure plan for the X-231B facility. No RD&D Permit was required.
- The closure of the X-231B facility was approved by Ohio EPA, requiring a performance standard of 70% mass removal. Actual mass removal was greater than 87% for the closure. A RCRA cap was placed on the surface.
- Specific permits for this technology must be worked out with the appropriate regulators.
 - Some type of air permit may be required because of the off-gas capture and treatment part of the system.
 - An underground injection permit might be required if the treatment is occurring below the water table.
 - CERCLA or RCRA permitting may be required.
 - At federal facilities a NEPA review may be required.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Potential worker safety risks for all the processes include those associated with standard drilling operations and potential exposure to VOCs and particulates in off-gas.
- Peroxide Injection: The hydrogen peroxide concentrations utilized were sufficiently low that it was not considered a hazardous material and its handling was of limited health and safety concern. While hydrogen peroxide at 5% by weight concentration is relatively harmless, it does require precautions in handling.

Community Safety

- ISESM with an operational off-gas treatment system does not produce any significant routine release of contaminants.
- No unusual or significant safety concerns are associated with transport of equipment, samples, waste, or other materials associated with ISESM.

Environmental Impacts

- ISESM disturbs the ground surface during operations. But because the site is remediated rapidly, long term effects are minimal.
- Operation of the equipment creates moderate noise in the immediate vicinity.

Socioeconomic Impacts and Community Perception

- ISESM has a minimal economic or labor force impact.
- The general public has limited familiarity with ISESM.



SECTION 7

LESSONS LEARNED

Design Issues

- The equipment utilized for all process components was commercially available. However, the equipment may need to be specially modified for a particular application.
- More recent experience suggests that an 8-ft. diameter auger may be optimum for this type of application.
- Hot Air Injection:
 - The orifices in the 2-arm, 10-ft. diameter tool were reduced to 0.25 in. from the ambient air size of 0.5 in. to increase the back pressure and enable maintenance of higher temperatures, thus encouraging further volatilization of contaminants.
 - A compressor operator was required to manually control system airflow, temperature, and pressure. However, the system has now been modified to be controlled automatically.
- Peroxidation:
 - Peroxide must be delivered by tank truck or rail car to meet required treatment processing.
- Solidification/Stabilization:
 - Laboratory treatability studies were performed to test the best grout formulation. The grout recommended contained 25% cement, 10% granular activated carbon, fly ash to increase fluidity and a retarder. Other more simple and less costly formulations have been successfully used at other locations.

Implementation Considerations

General observations regarding operation of each treatment process tested at the X-231B site.^a

Technology	Soil treatment rate ^b	Operational simplicity and stability	Safety issues	Secondary waste generation
Hot air vapor stripping	~15 c.y. per hour.	Only requires an air compressor.	Heavy equipment operation; compressed hot air.	Off-gas and decontamination fluids.
Ambient air vapor stripping	~15 c.y. per hour.	Only requires an air compressor.	Heavy equipment operation; compressed air.	Off-gas and decontamination fluids.
Peroxidation	~45 c.y. per hour.	Requires chemical injection system	Heavy equipment operation; H ₂ O ₂ ; compressed air.	Off-gas, excess H ₂ O ₂ , and decontamination fluids.
Solidification	~45 c.y. per hour.	Requires grout injection system.	Heavy equipment operation; grout handling equipment.	Off-gas, excess grout, and decontamination fluids.

^a The information shown is preliminary and intended for general comparison only.

^b Soil treatment rates (per equipment operating) were estimated assuming a process treatment efficiency of 70 to 95%.

- Injection of grout for solidification/stabilization required adjustments, including those made in the field. The grout formulation was adjusted by:
 - changing from powdered to granular activated carbon,
 - adding fly ash to increase the consistency and fluidity of the grout,
 - adding a retarder to provide a working time of 2 hours,
 - adding water to the grout at the site to further increase workability.



- In situ solidification of contaminated soil materials was more complicated than originally anticipated. This was due in part to the difficulty in effectively mixing the dense clay soils in situ and to delivering the proper volume of grout of the appropriate formulation. There are likely to be infield adjustments to the grout formulation and injection volume after working knowledge of the grout delivery system and the site conditions are acquired. Field experience since the demonstration has improved the process to make it more effective and efficient.
- Generation of secondary liquid wastes, namely waste grout from the delivery trucks and from rinsing out the mixing equipment, could be appreciable in the solidification process operation. An improved "grout-on-demand" system has been developed to minimize waste.

■ Technology Limitations/ Needs for Future Development

- Potential enhancements to the ISESM approach include:
 - ◊ more mobile and scaled down mixing equipment
 - ◊ more efficient coupling of treatment processes
- Other technologies may be coupled to the ISESM process as a post-soil mixing enhancement:
 - ◊ passive treatment processes for in situ treatment
 - ◊ soil vapor extraction
 - ◊ bioremediation
- Other reagent additives should be examined as alternatives:
 - ◊ other oxidants (e.g., permanganate, ozone)
 - ◊ reductants (e.g., zero-valence metals)
 - ◊ sorbents (e.g., peat or zeolites).
- Improvements in equipment and experience will eventually reduce costs further.

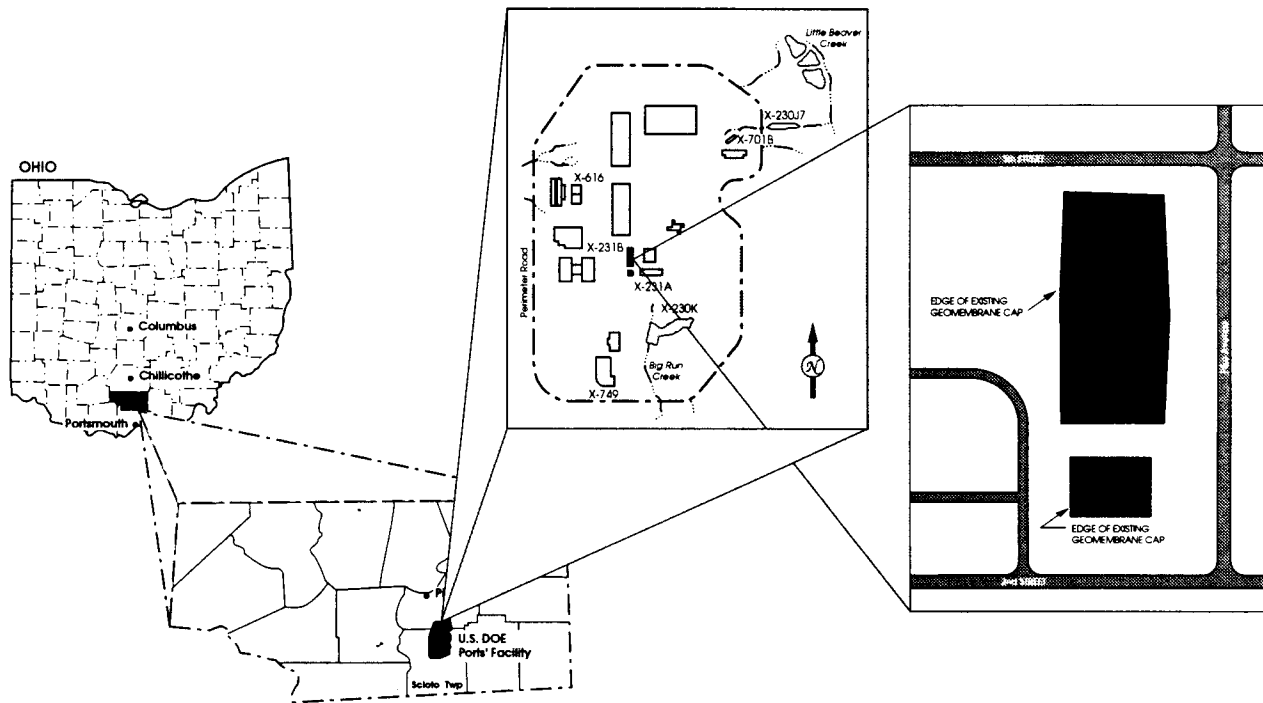


APPENDIX A

DEMONSTRATION SITE CHARACTERISTICS

Background

- The DOE Portsmouth Gaseous Diffusion Plant is located approximately 70 miles south of Columbus in southern Ohio.



Location of the DOE Portsmouth Gaseous Diffusion Plant and the X-231B Unit

- The X-231B waste management unit consists of two adjacent waste oil biodegradation areas. The X-231B Unit encompasses about 0.8 acres and was reportedly used from 1976 to 1983 for the treatment and disposal of waste oils and degreasing solvents, some containing uranium-235 (^{235}U) and technetium-99 (^{99}Tc). TCE and other VOCs remained in the soil and spread into the shallow ground water.



Site Characterization

- Physical, chemical and biological properties of subsurface soil at the X-231B site as measured in samples collected in 1990.

Characteristic ^a	Nominal depth and boring location					
	Shallow (7-ft depth)			Deep (17-ft depth)		
	SB01	SB02	SB03	SB01	SB02	SB03
Depth, ft	7.2	6.2	6.2	17.2	17.2	17.2
Particle size distribution:						
Clay: <0.002 mm, wt%	22.5	na	25.0	14.0	12.0	15.0
Silt: 0.002-0.05 mm, wt%	65.5	na	67.0	64.0	55.0	39.0
Sand: 0.05-2.0 mm, wt%	12.0	na	8.0	22.0	33.0	46.0
Water content, dry wt %	17.6	na	19.0	23.5	23.5	22.0
Percent solids, wt%	86.6	na	81.0	81.8	81.0	81.2
pH	5.32	na	5.96	7.40	6.16	7.01
Total organic carbon, mg/kg	579	na	1190	245	184	472
Kjeldahl nitrogen, mg/kg	<500	na	<500	<500	<500	<500
Total phosphorus, mg/kg	66	na	66	66	73	108
Total sulfur, mg/kg	24	na	<10	23	30	<10
Exchangeable cations: ^b						
Calcium, mg/L	47	na	48	60	37	71
Magnesium, mg/L	42	na	31	28	25	34
Sodium, mg/L	9.4	na	6.0	10.6	3.1	15.1
Potassium, mg/L	6.3	na	4.5	6.0	4.0	5.0
Percent moisture ^c , wt%	17.9	18.7	20.1	23.0	23.5	23.4
Liquid limit ^c , wt%	na	na	na	25.30	25.55	25.73
Plastic limit ^c , wt%	na	na	na	22.19	22.63	20.56
Plasticity index ^c , wt%	na	na	na	3.11	2.92	5.17
Total bacteria, CFU/g	2.26E04	2.37E05	1.02E04	<1E02	<1E02	<1E02
Methanotrophs,	Detected	Detected	Detected	Not Detected	Not Detected	Not Detected

na Indicates analyses not performed.

^a Results of analyses are expressed on a field moist soil weight basis unless otherwise indicated.

^b Averages of duplicate analyses; coefficient of variation for duplicates was <5%.

^c Percent moisture (wet wt. %) analyses performed by Geraghty & Miller, Inc., Dublin, Ohio.

- Contaminants of Concern

- ◇ Soil

- Thirteen VOCs were identified with the following being most prevalent and at the highest concentrations (i.e., several hundred to several thousand micrograms per kilogram).
 - trichloroethylene (TCE)
 - 1,1,1-trichloroethane (TCA)
 - 1,1-dichloroethylene (1,1-DCE)
 - methylene chloride
 - The highest concentrations were found in the unsaturated zone (~7-ft depth) near the center of the plot.
 - Low levels of ²³⁵U and ⁹⁹Tc are also present.

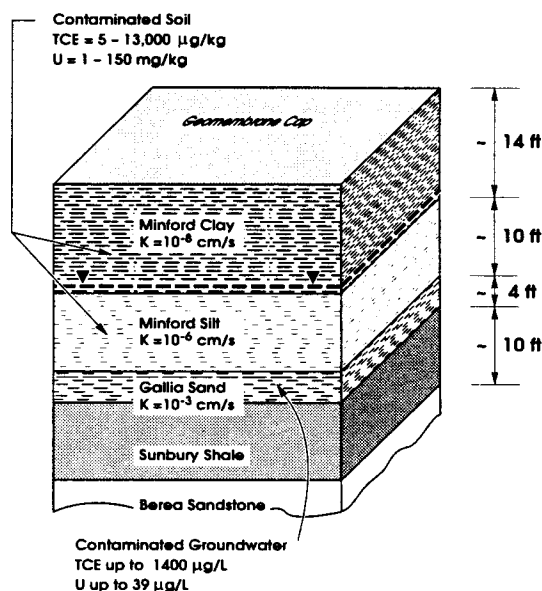
- ◇ Ground water

- The shallow ground water was also contaminated with some contaminants at levels well above drinking water standards.



Contaminant Locations and Hydrogeologic Profiles

- Ground water underneath the X-231B unit occurs in two aquifer systems: the Minford/Gallia Members and the Berea Sandstone. Existing site characterization data revealed that beneath the X-231B unit were fluvio-lacustrine silts and clays (Minford Member of the Teays Formation) underlain by silty sand and gravel (Gallia Member). The Gallia Member lies at a depth of approximately 25 ft and typically does not exceed 4 ft in thickness. Bedrock below the Gallia is the Mississippian age Sunbury Shale. The Sunbury Shale is 10 to 12 ft thick, slightly fractured, and has very low permeability. The water table in this area is approximately 10 to 14 ft below ground surface (bgs). Ground water flow occurs vertically through the Minford Member into the Gallia Member where flow is predominantly horizontal to the southeast toward a surface impoundment.



Subsurface characteristics beneath the X-231B Unit.

- Thirty-six groundwater monitoring wells have been installed in the vicinity of the X-231B unit. Twenty-five wells have been installed and screened within the Gallia deposit, but only three wells have been screened in the overlying Minford. Eight wells penetrate into the underlying bedrock (i.e., Sunbury or Berea).
- The hydraulic conductivities of all the shallow units are low. Laboratory measurements revealed a saturated hydraulic conductivity (K_{sat}) of only 0.00023 feet per day (ft/d) for the Minford clay and 0.0043 ft/d for the Minford silt. Field pumping tests yielded a substantially higher mean K_{sat} for the Gallia deposit of 7.1 ft/d. The lower portion of the Minford is in hydraulic continuity with the Gallia.
- The permeability of the Sunbury Shale is believed to be very low. Although thin and slightly fractured, the Sunbury may hydraulically isolate the underlying Berea from the overlying unconsolidated aquifer (i.e., Minford/Gallia).
- Several VOCs (e.g., TCE and 1,1,1-TCA) are present throughout the Minford Member under the X-231B site from the ground surface to approximately 25 ft bgs. These same contaminants are present in the shallow ground water underneath and up to 750 ft downgradient from the X-231B Unit boundaries. The primary soil and ground water contaminant is TCE, which is present in the ground water at levels above federal drinking water standards.
- The Minford deposit beneath the X-231B Unit extends from the ground surface to approximately 22- to 24-ft depth. The Minford is comprised of an upper zone (top 12 ft or so) that is finer textured than the lower zone. Intensive sampling and analysis of the Minford deposit was conducted to delineate the contaminant distribution throughout the deposit to enable development of the treatment locations for the field test. Analysis of the results of this work revealed that approximately 78% of the VOCs are located in the upper 12 ft, above the water table. As a result, the field test was designed to focus on treatment of the unsaturated portion of the Minford deposit (i.e. the upper 15 ft). In addition, a single test was conducted to a depth of approximately 22 ft to provide some operational information for treatment of the lower Minford deposit, located below the water table.

APPENDIX B

TECHNOLOGY DESCRIPTION/PERFORMANCE DETAIL

Summary of Operating Conditions

Operating Parameters	Units	Hot Air Stripping	Hot Air Stripping - Deep	Ambient Air Stripping	Peroxidation Destruction	Solidification Stabilization
Auger rotation speed	rpm	5 to 10	5 to 10	5 to 10	5 to 10	5 to 10
Auger vertical movement rate	fpm	1	1	1	1	1 to 3
Mixed region diameter	ft	10	10	10	10	10
Mixed region depth	ft	15	22	15	15	15
Mixed region volume	cf	1180	1730	1180	1180	-
Air delivery rate	cfm	1000-1400	1000-1400	1000-1400	800	0
initially, reduced to 300						
Air exchange in soil column	RV/min	0.8 - 1.2	0.6 - 0.8	0.8 - 1.2	-	-
Air temperature at the source	°F	250	250	90	90	-
Air pressure at the source	psig	180	180	100	80	-
Shroud vacuum	in. H ₂ O	~ 5	~ 5	~ 5	-	~ 5
Peroxide injection rate	gpm	-	-	-	7.5	-
Peroxide injection volume	vol./vol.	-	-	-	ave. of 0.07	-
Peroxide concentration	wt%	-	-	-	5	-
Grout injection rate	vol. %	-	-	-	-	30
Off-gas flow rate	cfm	-	-	-	-	100-120
Treatment cycles						
0 to 7 ft zone	down/up	8	8	8	2	
7 to 15 ft zone	down/up	4	4	4	1	
0 to 15 ft zone	down/up					3 to 4
Treatment time per column	min	225	225	225	75	30 to 45

-	approximately	cf	cubic feet
cfm	cubic feet per minute	fpm	feet per minute
gpm	gallons per minute	°	degrees Fahrenheit
in H ₂ O	inches of water	min	minutes
psig	pounds/square inch (gauge)	RV/min	reactor volumes/minute
vol%	per cent by volume	wt%	per cent by weight



Treatment Performance: General Observations

General Observations for Each Treatment Process Tested at the X-231B Site.

Technology and components	VOC treatment process	VOC removal efficiency	Effect on non-VOC contaminants	Effect on soil properties	Effect on unmixed adjacent soil
Hot Air Vapor Stripping. An air compressor to deliver ~1400 cfm of 250°F air through a hollow kelly bar via jets in a 10 ft. auger.	Mass transfer and advective removal for ex situ capture and destruction	>95% mass removal after 3.75 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Limited if any; stimulation of biological activity and possible degradation of SVOCs	Disrupts natural soil structure. Injection of hot air stimulated some increased biological activity.	Limited impact on soil gas concentrations or pressure.
Ambient Air Vapor Stripping. An air compressor to deliver ~1400 cfm of 90°F air through a hollow kelly bar via jets in a 10 ft. auger.	Mass transfer and advective removal for ex situ capture and destruction	>90% mass removal after 3.75 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Limited if any; stimulation of biological activity and possible degradation of SVOCs	Disrupts natural soil structure. Injection of air stimulates markedly increased biological activity.	Limited impact on soil gas concentrations or pressure.
Peroxidation. An air compressor to deliver ~300 cfm of 90°F and 7% v/v addition of 5 wt% H ₂ O ₂ in air through a hollow kelly bar via jets in a 10 ft. auger.	H ₂ O ₂ interacts with soil Fe to oxidize VOCs in situ. Limited VOCs in off-gas are captured for destruction	>70% mass removal after 1 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Increased binding of metals. Preoxidation of SVOCs for biodegradation.	Mixing disrupts natural soil structure. Injection of H ₂ O ₂ does not "sterilize" soil. H ₂ O ₂ can reduce soil permeability of clays.	Limited impact on soil gas concentrations or pressure.
Solidification. An injection system to deliver ~1.5 cfm of 30% v/v (20% wt/wt) grout through a hollow kelly bar via jets in a 10 ft. auger.	Grout solidifies the soil and immobilizes the VOCs in situ. Limited VOCs in off-gas are captured for destruction by either carbon adsorption, catalytic oxidation, biotreatment, etc.	>90% apparent capture of VOCs in preset grout/soil mix after 1 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Encapsulation and stabilization of metals in grout.	Mixing disrupts natural soil structure. Injection of grout reduces permeability significantly.	Limited impact on soil gas concentrations or pressure.

Treatment Performance: Post-demonstration Soil Chemical Analyses

Results of selected TCLP analyses of grouted soil after in situ solidification.

Target analyte	Cores collected at 15 months (mg/L) ^a		Post-demonstration grout soil samples (mg/L) ^b		TCLP Limits (mg/L)
	4-5 ft. depth	8-9 ft. depth	4-5 ft. depth	8-9 ft. depth	
Carbon Tetrachloride	< 0.025	< 0.025	< 0.15	< 0.15	0.5
Benzene	< 0.025	< 0.025	< 0.09	< 0.09	0.5
1,2-Dichloroethane	< 0.025	< 0.025	< 0.10	< 0.10	0.5
Trichloroethylene	0.08	< 0.025	< 0.22	< 0.22	0.5
Barium	9.4	2.9	...	...	100.0
Lead	< 0.05	< 0.05	...	...	5.0
Uranium	< 0.0004	< 0.0004	...	...	...

^a Samples collected 15 months after in situ solidification in August 1993 and analyzed at ORNL Analytical Chemistry Division.

^b Samples collected immediately following in situ solidification in May 1992 and analyzed at the Clemson Technical Center, Clemson, South Carolina.



Treatment Performance: Physicochemical Properties of Soil, Pre-and Post-Demonstration

Physicochemical properties of the untreated and solidified X-231B soil.

Sample description	Sample depth (m)	Water content (wt%) ^a	Bulk density (g/cm ³)	Compressive strength (kPa)	Hydraulic conductivity ^b (cm/sec)
Untreated control core	0.3-0.6	20.5 ^c			
	1.2-1.5	16.9 ^c	2.15	...	8.08x10 ⁻⁸
	2.4-2.7	18.4 ^c	1.75	...	...
	3.9-4.2	16.5 ^c	...	...	8.09x10 ⁻⁸
S/S core	0.3-0.6	19	1.73 ^c	5200 ^d	8.88x10 ⁻⁶
	1.2-1.5	23.5	1.66 ^c	3500	...
	2.4-2.7	19	1.72	2600	...
	3.9-4.2	13.6	2.00 ^c	390	7.75x10 ⁻⁶

^a Analyses performed at 60°C.

^b All values represent at a minimum, the average of 6 replicate analyses. Data reported at 25°C per ASTM D5084. Permeant fluid = 0.005M CaSO₄.

^c Average of analyses of two samples.

^d Sample taken at the 1-m depth.



APPENDIX C

TECHNOLOGY SELECTION DETAIL

Technology Selection

Selection of the most promising technologies for demonstration at X-231B was accomplished by a ration ranking process. The approach enabled rigorous evaluation of each technology and provided results regarding implementation, operation and maintenance, performance and cost. The following table summarizes key information from this process for comparison of technologies.

Technology	Estimated Time for Installation & Operation	Processing Rates	Minimization of Full-scale Remediation Costs ^a
In situ immobilization	1 month	1000 cy/d	54
In situ hot air/steam stripping	rapid	3 to 10 cy/hr	50
In situ electrokinetics	additional research required prior to VOC application	N/A ^b	38
In situ jet mixing and slurry reactor	1 month	N/A ^b	46
In situ electromagnetic or radiofrequency energy heating	5 months (3 mo. installation, 2 mo. operation)	20 cy/d for demo 200 tons/d full scale	39
In situ (ex situ) hydrogen peroxide	Installation about 1 week, operation about 1 month	100 cy/d	39
Ex situ thermal desorption	5 months to 2 years	100 to 200 tons/d full scale	34
Ex situ immobilization	1 months	10,000 to 20,000 cf/d	49

^a Score listed is the result from the ranking process. The higher the score the greater the ability of the technology to minimize full-scale remediation costs.

^b Not done to remove VOCs at the time of this demonstration.



APPENDIX D

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